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Compressive strength of wire-woven bulk kagome with various orientations

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Abstract

To date, the mechanical behavior of WBK under compression has been studied for a certain orientation in which WBK is presumed to have the highest strength. In this study, the compressive strength of WBK various orientation are presented. First, analytic solutions are derived with consideration of wire waviness and brazed joints at the cross points among wires. Numerical simulations are performed with a unit cell model with periodic boundary conditions. Compressive strengths depending on the orientation estimated by the approaches are compared with experimental results on failure maps to prove the validity. Practical and physical meanings of the results are discussed.
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1. Introduction

WBK, which stands for Wire-woven Bulk Kagome, is a kind of cellular metal with a regular truss structure (Lee (2007)). Helically formed wires are spin-inserted in six directions and are evenly distributed in space to assemble a 3D Kagome truss-like structure. The assembly is brazed at high temperature so that the molten filler metal can concentrate at the intersections by capillary force to fix the intersections. WBK composed of stainless steel wires was investigated to determine the effects of number of layers, slenderness ratio of struts, and in-plane size on the strengths of WBK (Lee et al. (Acta Materialia, 2009), Lee et al. (Composite Structures, 2009)). WBK can be

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assembled by wires of various materials such as aluminum alloys, spring steel, titanium, stainless steel tubes, and even fiber reinforced composites (Lee et al. (Advanced Engineering Materials, 2009), Lee et al. (Scripta Materialia, 2009), Lee et al. (2012)).

However, the strength of WBK has always been studied for a specific orientation in which WBK is presumed to have the highest strength. Because WBK has open cell architecture, it could be used as sandwich cores to replace honeycombs, in which case its stiffness as well as its strength becomes important (Allen (1969)). To determine stiffness, the displacement of WBK needs to measure accurately because the elastic deformation of a specimen before a yield point is likely to be infinitesimal.

Recently, the authors have performed a large industry-university joint research on the feasibility of application of WBK-cored sandwich panel for ship building (Kang (2012)). As a part of the results, this article presents mechanical properties of mild steel WBK cores under compression. The effects of orientation on the equivalent strength and equivalent Young's modulus of WBK are evaluated. Basic theories are introduced, and experimental and numerical results are presented.

2. Theory

Fig. 1 depicts the configurations of WBK in three different orientations under compression on the top, i.e., in z, y, and x-directions, respectively. For the realistic configuration of WBK core with helically curved struts and filler metals brazed at the intersections of wires, Lee at al. (Mechanics of Materials, 2013) derived the complex mathematical solutions for the equivalent strength and Young's modulus of WBK in z-orientation, assuming elastic-perfectly plastic wires. If the equivalent strength and modulus of WBK are written as follows:

$$\bar{\sigma}_o^z = \frac{\sqrt{2}}{8}\pi\sigma_{ow}\left(\frac{d}{c}\right)^2 \tag{1a}$$

$$\bar{E}^z = \frac{3\sqrt{2}}{40}\pi E_w\left(\frac{d}{c}\right)^2 \tag{2a}$$

where σ_{ow} and E_w are the modified yield strength and Young's modulus of the struts, considering the helically curved wires and the filler metals brazed at the intersections. For the ideal Kagome truss composed of straight struts and frictionless joints, the modified yield strength and Young's modulus of the struts become the intrinsic properties of wire material, i.e., $\sigma_{ow} = \sigma_o$ and $E_w = E$, and the above equations become to be the same as those derived by Lee et al. (Materials and Design, 2009). In this paper, the mathematical solutions derived in another paper by Lee et al. (2013) were used to calculate σ_{ow} and E_w according to the slenderness ratio of struts, *d/c*, for seven different sizes of the brazed zone with respect to the wire diameter, *B/d*. The other two orientations assumed that the yield strengths and Young's moduli of struts composing WBKs can be modified in the same way. Accordingly, the equivalent strengths and equivalent Young's moduli of WBK in y and x-orientations can be written as follows:

$$\bar{\sigma}_o^y = \frac{3\sqrt{2}}{32}\pi\sigma_{ow}\left(\frac{d}{c}\right)^2 \text{ for y-orientation, and} \tag{1b}$$

$$\bar{\sigma}_o^x = \frac{\sqrt{2}}{16}\pi\sigma_{ow}\left(\frac{d}{c}\right)^2 \text{ for x-orientation} \tag{1c}$$

$$\bar{E}^y = \bar{E}^x = \frac{\sqrt{2}}{16}\pi E_w\left(\frac{d}{c}\right)^2 \text{ for y \& x-directions} \tag{2b}$$

3. Experiments

3.1. Specimen Preparation

Zinc plated wires of low carbon mild steel were used to fabricate WBK specimens. First, the wires were formed into a helix by using a specially designed wire twister (Lee et al. (Advanced Engineering Materials, 2009)). The helical wires were manually assembled into wire-woven metal with 3D Kagome-like structure, namely WBK. The detailed assembly process is given in Lee et al. (2007). The assembly was dipped into 50% concentrated hydrochloric acid (HCl) and washed out zinc coat on the surface. Then an aqueous mixture of copper brazing paste

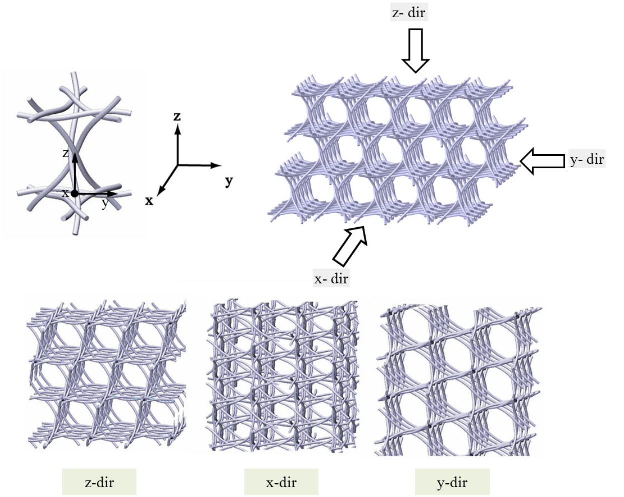

Figure 1. Configurations of WBK in three orientations

(CHEM-TECH Korea, 17LR-283) was sprayed over the assembly. The assembly was dried in an oven at 110 °C, and heated to be brazed at 1120 °C in the de-oxidation atmosphere of H2-N2 mixture. The brazed WBK cores were trimmed and ground to flatten the upper and lower surfaces. Finally, mild steel plates of 10mm thickness were bonded to the cores by secondary brazing.

The specimens were prepared in three different orientations, that is, z, y, and x-orientations, depicted in Fig. 1. The diameter, pitch, and helical radius of the helical wires were constant, d= 0.7mm, $2c$= 13.3 mm, and r_h= 0.424 mm. Hence, the slenderness ratio of the struts composing the WBK cores was d/c= 0.105. Once the WBK cores were fabricated by the assembly and brazing process, the top and bottom surfaces for each orientation were machine-flattened by trimming and grinding before their secondary brazing with the thick face plates. Fig. 2 depicts the front views of the specimens installed in the test machine. Each WBK core was located in a volume of 100mm width x 100mm depth x 32.7mm height between the upper and lower face plates. Each core comprised about 7 x 7 cells in a layer, and 3 layers in the height.

3.2. Experimental procedure

For measurement of the material properties of the wires, separate wires were heat-treated during the thermal cycle of the brazing process, and tensile tests were performed with the wires wound around pins at both ends. An extensometer was installed along each specimen to measure strain.

Each WBK specimen was installed between a pair of large platens. The lower platen was supported by well-lubricated spherical (90 mm diameter) contact to compress the specimen evenly to apply uniform stress over a plane. Then the load was applied by displacement control at 0.002 mm/second. The load-displacements were monitored by a digital data logger, and the images of the specimen were monitored by a digital camera. As mentioned above, two clip gages were attached on opposite sides of the specimen by knife edges mounted across the upper and lower thick plates. The clip gages were home-made and calibrated according to ASTM standard E399. The displacements measured by the two clip gages were averaged to give the mean strain data over the volume of the WBK core. The equivalent Young's modulus of WBK core of each specimen was obtained from the linear part of stress-strain curve from the unloading process, which was carried out before the load reached to the peak.

4. Results

Fig. 3 depicts stress-strain curves measured from the tensile tests with the wires used to fabricate the WBK cores. The yield strength of the wires was σ_o = 224 MPa in average.

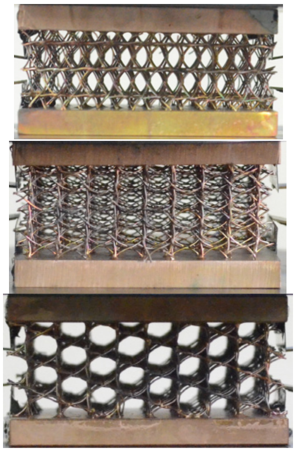

Figure 2. Front views of the specimens with WBK cores in *z, y, x*-orientations (from the top)

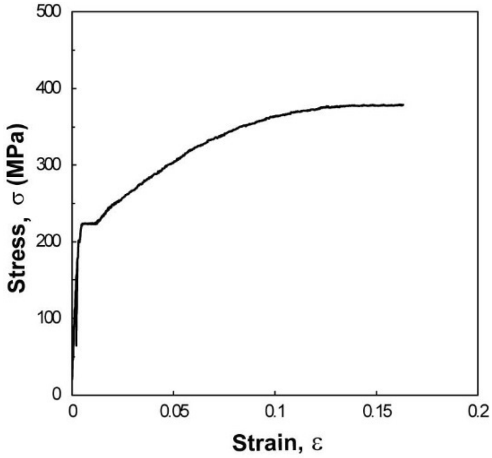

Figure 3. Stress-strain curves measured from tensile test for wires used to assemble WBK specimens

Fig. 4 depicts the equivalent stress - strain ($\bar{\sigma} - \bar{E}$) curves measured from the compression tests of the WBK cores with three different orientations. The equivalent Young's modulus was measured by unloading around the initial yield point by about 30% of the load level at which the specimen started to be unloaded. The figure includes also the equivalent stress - strain curves estimated from the FEA performed in the authors' preliminary study, and the equivalent strengths estimated by Eqs. (1a) to (1c), derived accounting for the curved struts and brazed filler metals in the intersections among wires. The equivalent peak strengths of the WBK cores were the highest in z-orientation, and the lowest in x-orientation. Namely, the equivalent peak strengths in y and x-orientations were measured to be about 3/4 and 1/2 of that in z-orientation, respectively, as estimated by the equations.

The peak strengths measured for the real specimens in z and y-orientations with curved struts and brazed filler metals at the intersections were significantly higher than the strengths estimated by Eqs. (1a) to (1c). Lee and Kang (Composite Structures, 2009) reported similar results for stainless steel WBKs, but the errors between the strengths measured for the real specimens and estimated by the equations were much higher than those observed for low carbon steel WBKs in this study. This difference seemed to be due to the higher strain hardening of the stainless steel (SUS 304) wires after the initial yield points than the low carbon steel wires. In fact, in the cases of the stainless steel wires, the strain hardening during plastic deformation after initial yielding induced the strength to increase up to more than twice of the initial yield strength at the strain of $\varepsilon = 0.1$, while, in the cases of the low carbon steel wires, the strain hardening induced the strengths to increase by about 50% at the same strain, as shown in Fig. 3. In Fig. 4, another set of equivalent stress–strain curves ($\bar{\sigma} - \bar{E}$) of the WBK models estimated by the FEA were based on the material properties shown in Fig. 3. The FEA results agreed well with those measured from the experiments, which verifies the FEA.

Figs. 5(a) to 5(c) depict again the equivalent stress - strain ($\bar{\sigma} - \bar{E}$) curves for the three orientations shown in Fig. 4 in a narrower range of strain, that is, up to $\bar{\varepsilon} = 2\%$. Each figure includes another stress-strain curve (green lines) estimated from a separate FEA performed with new material properties without strain hardening, i.e., with elastic-perfectly plastic material properties. And also, the equivalent strengths estimated by Eqs. (1a) to (1c), in which the yield strength of the wires themselves was modified from that measured from the tensile tests by a factor of σ_{ow}/σ_o = 0.68 for d/c=0.1 and B/d=1.7 (Lee et al. (Composite Structures, 2013)), taking into account helically curved struts and filler metals brazed at the intersections of wires, are indicated by the horizontal dashed lines. The peak strengths from the new stress-strain curves obtained with elastic-perfectly plastic material properties agreed fairly well, particularly in x-orientation, with the equivalent strengths estimated by Eqs. (1a) to (1c). Recalling that the equations were derived by assuming an elastic-perfectly plastic material (Lee et al. (Mechanics of Materials, 2013),

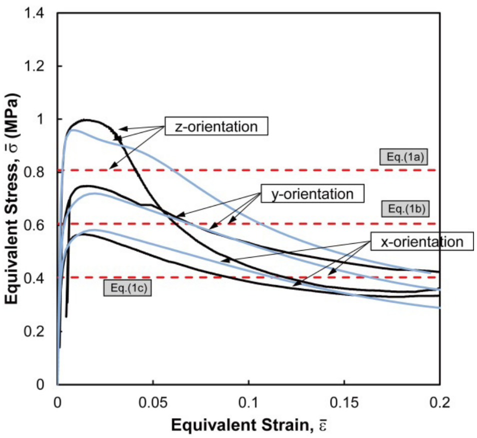

Figure 4. Equivalent stress – strain curves measured from compression tests of WBK cores

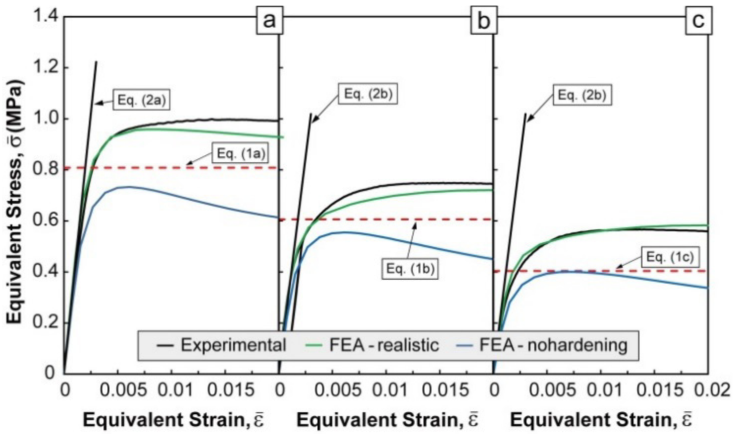

Figure 5. Equivalent stress – strain curves for three orientations in strain range up to $\bar{\varepsilon}$ = 2%.

these agreements proved the validity of the equations. It can be concluded that the higher strengths observed in the experiments were due to the strain hardening of the wires, as presumed above. That is, the strength deterioration due to the curved struts was substantially compensated by the strain hardening of the wires.

In each of Figs. 5(a) to 5(c), the straight lines starting from the origin of the coordinate system denote the equivalent Young's modulus of the WBK cores, $\bar{E}$, estimated by Eq. (2a) or (2b), in which the Young's modulus of the wires themselves (E = 200 GPa) was modified by a factor E_w/E = 0.64 for d/c= 0.1 and B/d= 1.7 (Lee et al. (Composite Structures, 2013)), taking account of the realistic configuration. The lines estimated by the modified equations well fit the initial slopes of the stress-strain curves. FEA was separately performed using purely elastic material properties to estimate the equivalent Young's moduli, $\bar{E}$. Despite the simple approach based on the tetrahedron model, Eq. (2a) or (2b) gave fairly good estimations with ± 10% error compared to FEA or experiments. Unlike Eq. (2b), the Young's modulus obtained from FEA or experiments for y-orientation was somewhat higher than for x-orientation. Nevertheless, it is concluded that WBK shows low variation in equivalent Young's modulus according to orientation.

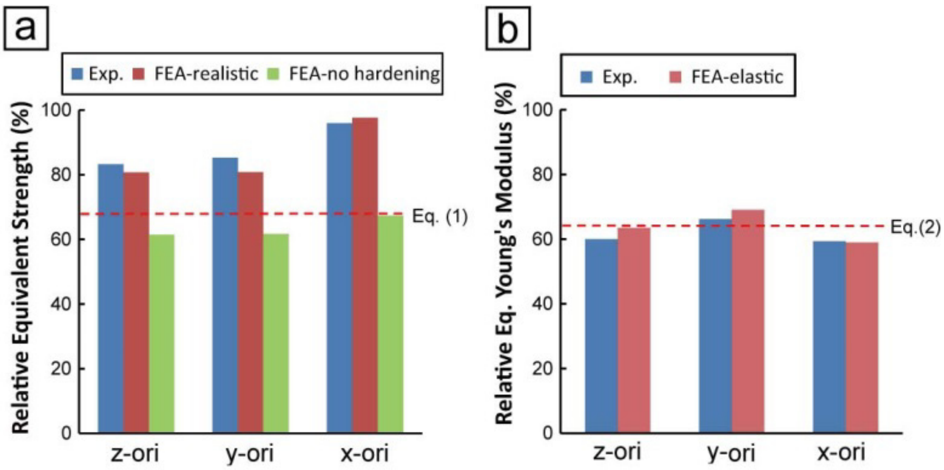

Figure 6. Equivalent strengths and equivalent Young's moduli of WBK cores relatively scaled in comparison to estimations by corresponding basic equations.

5. Discussion

Figs. 6(a) and 6(b) summarize the equivalent strengths and equivalent Young's moduli of the WBK cores mentioned above. In each figure, the equivalent strengths or Young's moduli were scaled relative to the estimations for ideal Kagome truss (Lee et al. (Composite Structures, 2013)). Fig. 6(a) shows that the modified equations accounting for the curved struts and brazed joints, Eqs. (1a) to (1c), gave the lower bound of the equivalent strength of WBK. On the other hand, Fig. 6(b) shows that the modified equations, Eqs. (2a) and (2b), gave the upper bound of the equivalent Young's moduli.

6. Conclusion

i) The equivalent peak strengths of the WBK cores in y and x-orientations were about 3/4 and 1/2 of that in z-orientation, respectively.

ii) Regardless of the orientation, the equivalent peak strengths estimated by the modified equations that accounted the curved struts and the brazed joints among wires agreed fairly well with those estimated by the corresponding FEAs that used elastic-perfectly plastic material properties.

iii) The modified equations of the equivalent Young's moduli accounting for the curved struts and brazed joints gave the upper bound in comparison to those measured from the experiments.

7. Acknowledgements

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